



TITLE:

Transient heat transfer from a wire to a forced flow of subcooled liquid hydrogen passing through a vertically mounted pipe

AUTHOR(S):

Tatsumoto, H.; Shirai, Y.; Shiotsu, M.; Naruo, Y.; Kobayashi, H.; Nonaka, S.; Inatani, Y.

CITATION:

Tatsumoto, H. ...[et al]. Transient heat transfer from a wire to a forced flow of subcooled liquid hydrogen passing through a vertically mounted pipe. IOP Conference Series: Materials Science and Engineering 2015, 101(1): 012177.

ISSUE DATE:

2015-12-18

URL:

<http://hdl.handle.net/2433/235616>

RIGHT:

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Transient heat transfer from a wire to a forced flow of subcooled liquid hydrogen passing through a vertically-mounted pipe

H Tatsumoto¹, Y Shirai², M Shiotsu², Y Naruo³, H Kobayashi³, S Nonaka³ and Y Inatani³

¹J-PARC Center, Japan Atomic Energy Agency, Tokai, Ibaraki, JP

²Department of Energy Science & Technology, Kyoto University, Kyoto, JP

³Institute of Space and Astronautical Science, JAXA, Kanagawa, JP

tatumoto@post.j-parc.jp

Abstract. Transient heat transfers from Pt-Co wire heaters inserted into vertically-mounted pipes, through which forced flow subcooled liquid hydrogen was passed, were measured by increasing the exponential heat input with various time periods at a pressure of 0.7 MPa and inlet temperature of 21 K. The flow velocities ranged from 0.3 to 7 m/s. The Pt-Co wire heaters had a diameter of 1.2 mm and lengths of 60 mm, 120 mm and 200 mm and were inserted into the pipes with diameters of 5.7mm, 8.0 mm, and 5.0 mm, respectively, which were made of Fiber reinforced plastic due to thermal insulation. With increase in the heat flux to the onset of nucleate boiling, surface temperature increased along the curve predicted by the Dittus-Boelter correlation for longer period, where it can be almost regarded as steady-state. For shorter period, the heat transfer became higher than the Dittus-Boelter correlation. In nucleate boiling regime, the heat flux steeply increased to the transient CHF (critical heat flux) heat flux, which became higher for shorter period. Effect of flow velocity, period, and heated geometry on the transient CHF heat flux was clarified.

1. Introduction

Liquid hydrogen is expected as a coolant for high- T_c superconducting devices because of its boiling point lower than that of liquid nitrogen, higher thermal conductivity, greater specific heat and low viscosity. The knowledge of transient heat transfer to liquid hydrogen in forced flow is necessary for its cooling design and stability during a quench. There has been a lack of systematic experimental data on forced-flow liquid hydrogen, although several workers investigated pool boiling heat transfer of liquid hydrogen [1-5].

Tatsumoto et al. [6] developed a thermal-hydraulics experimental system for liquid hydrogen to conduct a systematic investigation of the forced-convection heat transfer of liquid hydrogen. They studied steady-state pool boiling [7,8] and forced convection heat transfer of saturated and subcooled liquid hydrogen [9-11]. Shiotsu et al. [12] studied transient heat transfer from a horizontal flat plate in a pool of liquid hydrogen. They reported that, unlike with liquid nitrogen, no direct transition from non-boiling to film boiling was observed. Tatsumoto et al. [13] measured a transient heat transfer from a wire, inserted into a vertically mounted pipe, to a forced flow of subcooled liquid hydrogen with an exponential increase in the heat generation rate at a pressure of 0.7 MPa. They reported that there was no direct transition in forced flow of liquid hydrogen as well as for pool boiling.



In this study, we measure the transient heat transfer from heated wires with various lengths that were inserted into vertically mounted pipes with various diameters to a forced flow of subcooled liquid hydrogen at a pressure of 0.7 MPa and inlet temperature of 21 K with an exponential increase in the heat generation rate, to clarify the effect of the heating, flow rates, and flow channel geometries on the transient critical heat flux (CHF).

2. Experimental apparatus and method

2.1. Thermal–hydraulic experimental system for cryogenic hydrogen

A liquid hydrogen experimental system has a design pressure of 2.1 MPa, and is installed in an explosion-proof laboratory as shown in Figure 1. Details of the experimental system and the measurement procedure have already been described in a previous study [1]. A main tank has an inner diameter of 406 mm and height of 1495 mm and is placed on a scale (Mettler Toledo WMHC 300s) that can be measured to 400 kg with a 0.002 kg resolution. The inventory of liquid hydrogen is 50 L. A receiver tank has an inner diameter of 310 mm and height of 1375 mm. The hydrogen inventory is 60 L and is slightly larger than that of the main tank. Three flow channels, in which Pt–Co wire heaters with various lengths are inserted, are connected in series at one end of a transfer line with a control valve having a C_v of 1.1. Liquid hydrogen in the main tank is pressurized to a desired value using pure hydrogen gas (99.999%) from hydrogen gas bottles controlled by a dome-loaded gas regulator. The receiver tank is maintained at atmospheric pressure by always opening a release valve. Stable forced flow can be produced by adjusting the control valve. The mass flow rate through the test heaters is estimated by measuring weight change of the main tank, and by measuring the flow rate of the hydrogen feed gas by using a turbine flow meter. Flow measurement error is estimated to be within 0.1 g/s for a 40 s measurement period [4].

2.2. Test heaters

In this study, we used three types test heaters. Figure 2 shows a wire heater inserted into a vertically mounted pipe. The wire heaters are made of Pt–Co alloy, and have the same diameter d of 1.2 mm and heated lengths L of 60 mm, 120 mm and 200 mm, respectively. The wire heaters are located on the central axis of the pipes with diameters D of 5.7 mm, 8.0 mm and 5.0 mm, respectively. Table 1 indicates dimensions of the wire heaters and the flow channels. The hydraulic equivalent diameters D_e are 4.5 mm, 6.8 mm and 3.8 mm, respectively. The equivalent heated diameters D_h are 25.9 mm, 52.1 mm and 19.6 mm, respectively. The aspect ratios L/D_h of the test heater for $L = 60$ mm and $D = 5.7$ mm are the same as that for $L = 120$ mm and $D = 8.0$ mm. The flow channel is made of fiber-reinforced plastic (FRP) for thermal and electrical insulation between the power cables and the transfer line. The entrance lengths of the flow channel are more than 10 times longer than the hydraulic equivalent diameter.

2.3. Experimental procedure

Details of the experimental procedure are presented in another paper [13]. The exponential heat generation of $Q = Q_0 \exp(t/\tau)$, where τ is the period, is applied to the Pt–Co wire heater using a fast-response direct-current source (24 V, 400 A max.), which is controlled to provide the desired time function for the heat input. The double-bridge circuit is first balanced at bath temperature. The output voltage of the bridge circuit, which is generated by the heater resistance change in the current heating, the voltage drop across the potential taps of the heater, and the voltage drop across the standard resistance are all amplified and simultaneously sampled at desired intervals. The average temperature of the heater is obtained from its electric resistance, which has been already measured using a double-bridge circuit in saturated liquid hydrogen and nitrogen. The heat generation rate is calculated from the measured voltage drops through the heater and the standard resistance. The surface heat flux q is the difference between the heat generation rate and time rate of change of the energy stored in the heater. The average surface temperature of the heater T_w is calculated from the average temperature and the

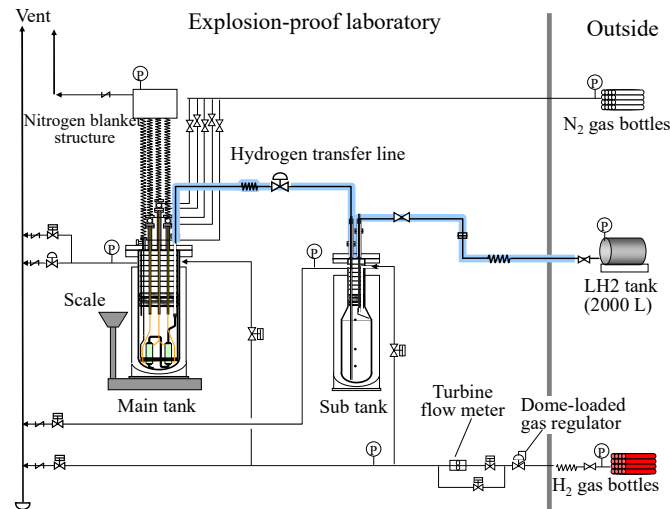


Figure 1. Schematic of an hydrogen experimental system.

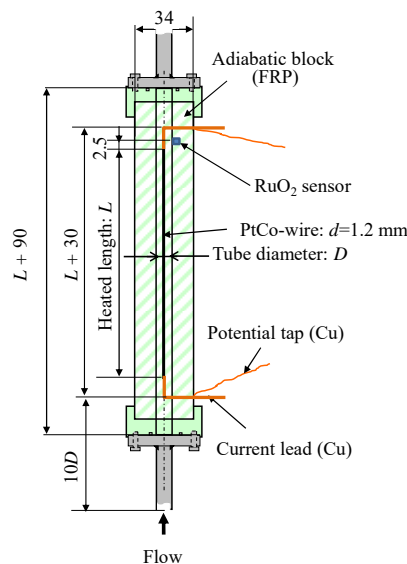


Figure 2. Schematic of test heater.

Table 1. Dimensions of the test heaters

No.	d	L	D	D_e	D_h	L/D_e	L/D_h
1	1.2	60	5.7	4.5	25.9	13.3	2.3
2	1.2	120	8.0	6.8	52.1	17.6	2.3
3	1.2	200	5.0	3.8	19.6	52.6	10.2

surface heat flux by solving a conduction equation in the wire's radius direction, although the temperature distribution would be generated along the length direction of the wire. The double-bridge circuit measuring the heater resistance has an accuracy of 1×10^{-4} . A temperature deviation of about 0.1 K can be measured by the bridge. The bath temperature and inlet temperature are measured by Cernox sensors with an accuracy of 10 mK. Only the temperature increment of the heater from the inlet temperature is necessary to perform the analysis. Accordingly, experimental error is estimated to be within 0.1 K of the heater surface temperature and within 2% of value of the heat flux.

We measured the transient heat transfer from the wire located on the center axis of the vertically mounted pipes to the forced flow of the subcooled liquid hydrogen at a pressure of 0.7 MPa and inlet temperature, T_{in} , of 20.9 K, by exponentially increasing the heat input, $Q_{0exp}(t/\tau)$. The exponential periods of the heat input were changed from 10.0 s to 19 ms. The inlet temperature corresponds to a subcooling temperature of 8 K. The flow velocities changes from 0.3 m/s to 7 m/s.

3. Results and discussion

3.1. Transient heat transfer characteristics

Figures 3 and 4 show transient heat transfer characteristics from Pt–Co wires with lengths of 60 mm and 200 mm placed on the central axis of pipes with diameters of 5.7 mm and 5.0 mm, respectively, to forced flow of subcooled liquid hydrogen flows at a pressure of 0.7 MPa and inlet temperature of 21 K. The transverse axis indicates an excess averaged heated surface temperature T_w beyond the inlet temperature $\Delta T_L (= T_w - T_{in})$. For relatively slow heating, the heat flux increases along a curve predicted by the Dittus–Boelter equation [14] to the onset of nucleate boiling, which appears at T_w slightly higher than T_{sat} of 29 K, and the heat transfer phenomenon can be regarded as steady-state. In nucleate boiling regime, with relatively little increase in ΔT_L , the heat flux steeply increases. At a certain upper limit heat flux for the nucleate boiling, called the CHF, the heat transfer characteristic changes to that in a film boiling regime. For low flow velocity, with a decrease in τ , the non-boiling heat transfer becomes higher than that predicted by the Dittus–Boelter equation because of the transient conductive heat transfer contribution. For faster flow velocity, the effect of sensible heat transport contribution becomes large, whereas the transient conductive heat transfer contribution seems to diminish. The transient nucleate boiling heat transfer is almost unaffected by the period of exponential heating. However, the transient CHF increases with a decrease in τ . Through the experimental data, we confirmed that, unlike with liquid nitrogen, forced convection heat transfer of subcooled liquid hydrogen has no direct transition from non-boiling to film boiling for shorter τ value as well as pool boiling of it [12].

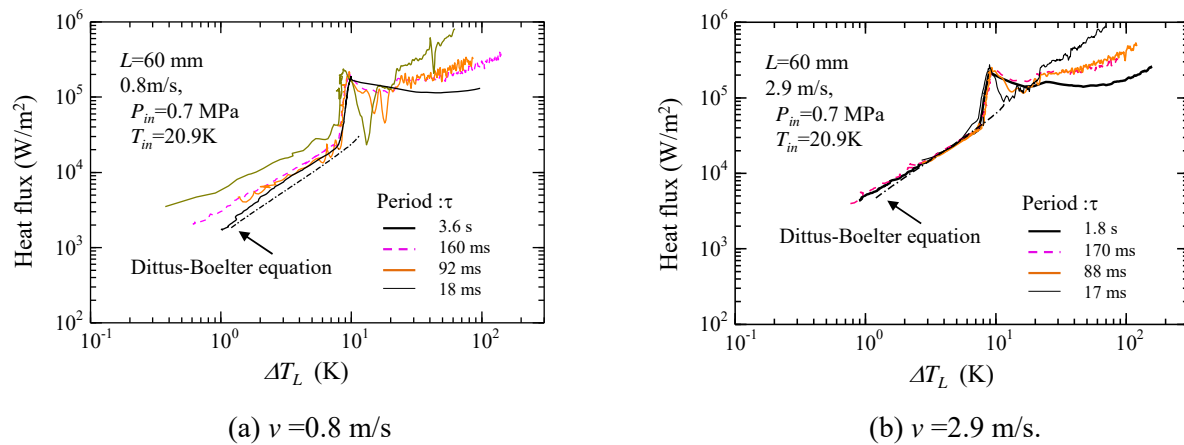


Figure 3. Transient forced convection heat transfer for $L = 60$ mm at 0.7 MPa under subcooled condition.

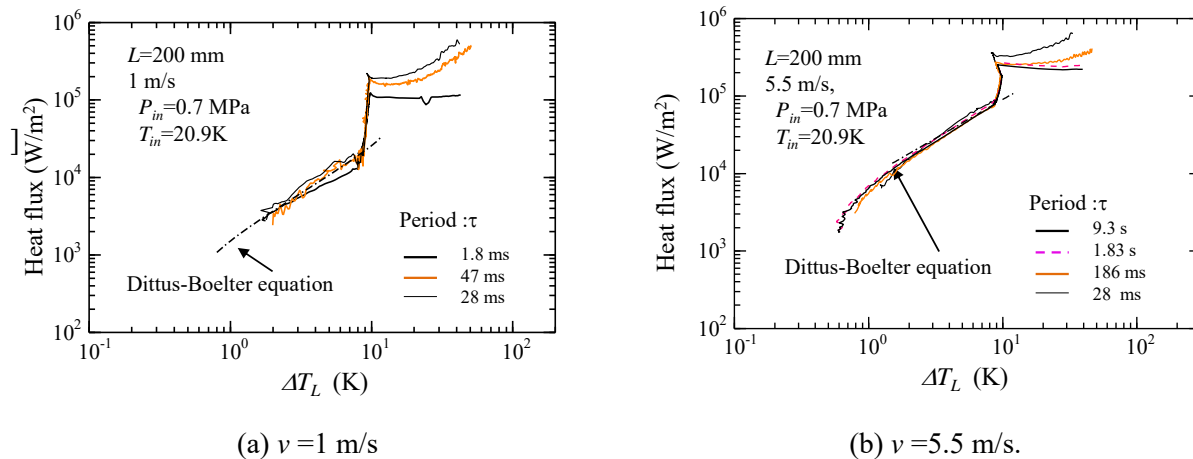


Figure 4. Transient forced convection heat transfer for $L = 200$ mm at 0.7 MPa under subcooled condition.

3.2. Non-boiling heat transfer coefficient

Figure 5 shows the effect of τ on the heat transfer coefficient in non-boiling region. For $L=120$ mm, the experimental data in previous study [13] are also shown in the figure. Sakurai et al. [15] measured transient heat transfer from a wire in a pool of liquid nitrogen with exponential heat generation, $Q_0 \exp(t/\tau)$. They reported that the following approximate transient conductive heat transfer coefficient h_c , which is higher than that of natural convection, can be expressed for shorter τ .

$$h_c = \left(\frac{k\rho C_p}{\tau} \right)^{0.5} \frac{K_1\left(\frac{\mu d}{2}\right)}{K_2\left(\frac{\mu d}{2}\right)} \quad (1)$$

$$\mu = \left(\frac{\rho C_p}{k\tau} \right)^{0.5} \quad (2)$$

where k is the thermal conductivity, ρ is the density and C_p is the specific heat. The subscript l indicates a liquid. K_1 and K_0 are the modified Bessel functions of the second kind of zero and first orders. For long τ values, the non-boiling heat transfer coefficients agree with those predicted by the Dittus-Boelter equation. For slow flow velocity, the heat transfer coefficient increases with a decrease in τ values due to the transient conductive heat transfer contribution, and approaches a curve given by equation (1). For higher flow rate, the steady-state heat transfer becomes higher. It seems that the effect would appear for even shorter τ values and the heat transfer coefficient is not affected by τ values in this experimental measurement range.

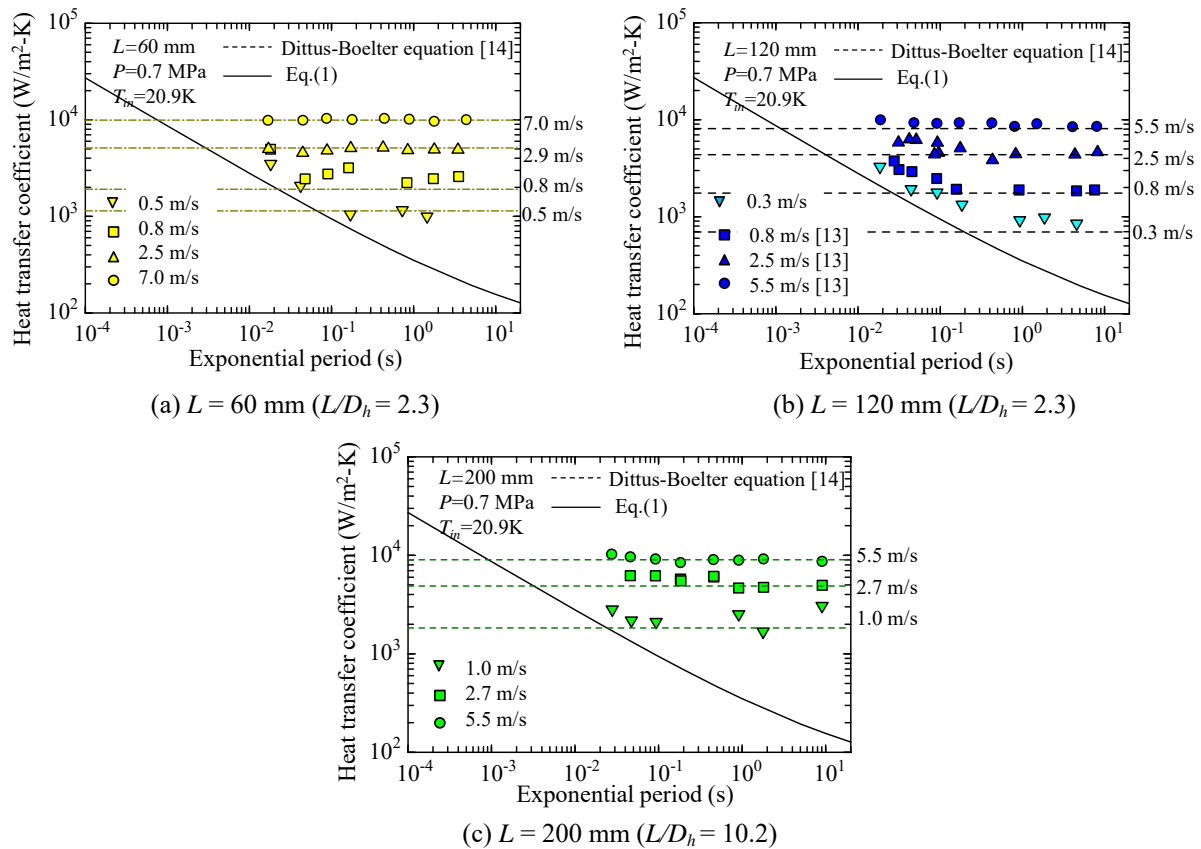


Figure 5. Effect of period τ on non-boiling heat transfer coefficient.

3.3. Critical heat flux

Figure 6 shows the effect of the flow rate on the steady-state critical heat fluxes, q_{st} . The steady-state CHF's increase, with an increase in flow velocity. They are higher for shorter L and smaller D , although the test heaters for $L = 60$ mm and 120 mm have the same aspect ratios L/D

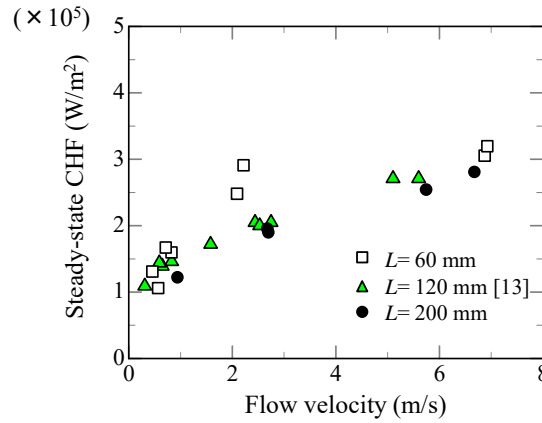


Figure 6. Effect of the flow rate on the steady-state critical heat flux

Figure 7 shows the effect of τ value on the transient CHF q_{cr} by the exponential heating at a pressure of 0.7 MPa. For the flow velocities higher than 1.0 m/s, the transient CHF's are almost

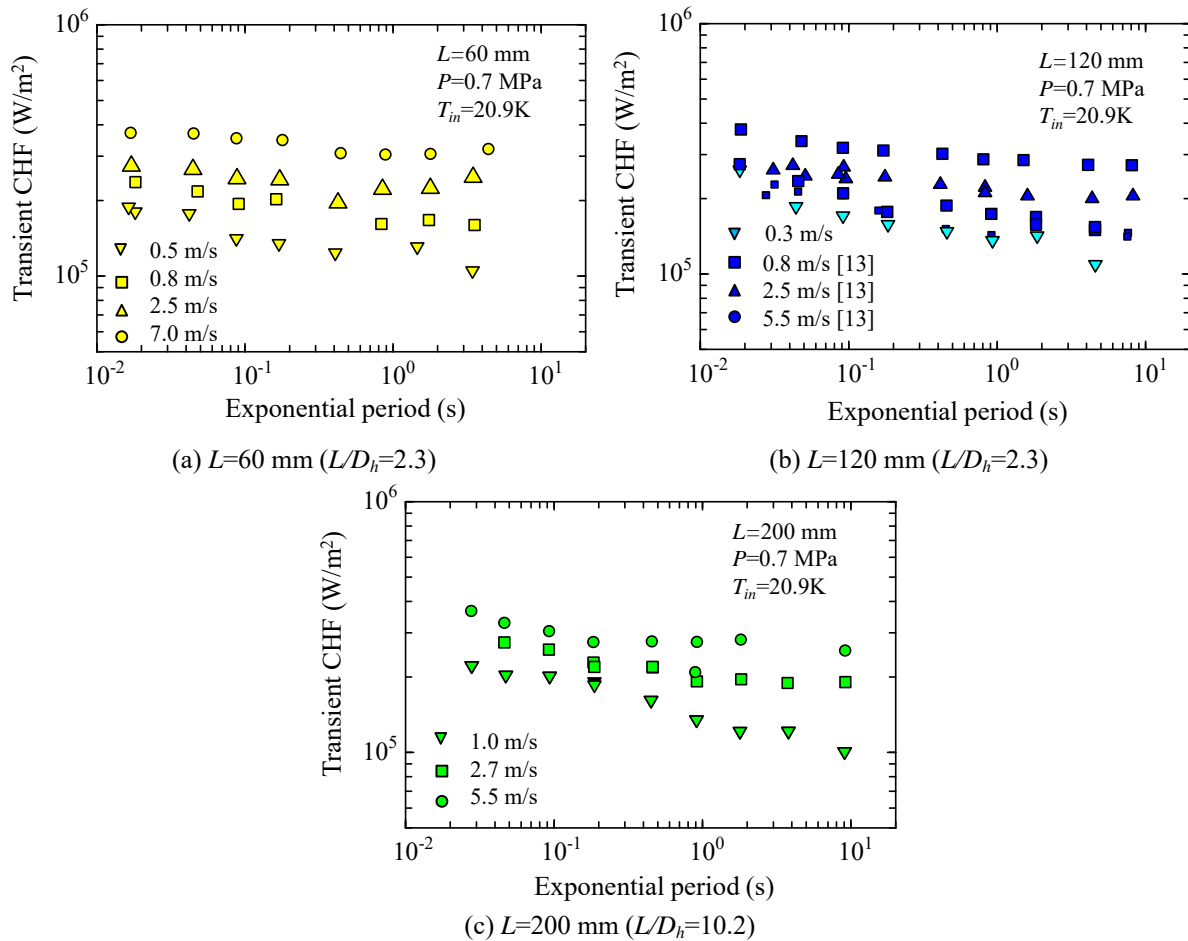


Figure 7. Effect of period τ on transient CHF.

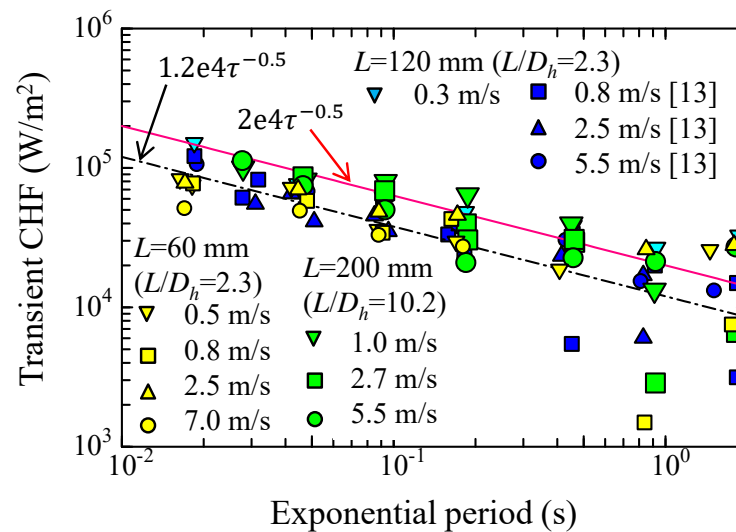


Figure 8. Effect of τ on the increase in q_{cr} from q_{st} .

unaffected by τ value for $\tau > 2$ s, and agree with the steady-state CHF. With a decrease in τ value from 2 s, the transient CHFs increase from q_{st} . At flow velocity lower than 1 m/s, although the transient CHFs are slightly affected by exponential heating rate for $\tau > 2$ s, they seem to approach the steady-state CHF.

Figure 8 shows the effect of τ on the increase of q_{cr} from q_{st} . The values of $q_{cr} - q_{st}$ are independent of the flow velocity for the same wire heater, and increases along the same curve with the gradient of $\tau^{-0.5}$ with a decrease in τ . For the same L/D_h , it seems that they exist on the same curve, although the steady-state CHFs are different. For larger L/D_h , although the value of $q_{cr} - q_{st}$ is larger, they seem to exist on the curve with the same gradient of $\tau^{-0.5}$.

4. Conclusion

We measured the transient heat transfer from wires inserted into vertically-mounted pipes with various aspect ratios of L/D_h to forced flow of subcooled liquid hydrogen by increasing the exponential heat inputs. The flow rates were varied from 0.3 m/s to 7.0 m/s at a pressure of 0.7 MPa and inlet temperature of 21 K, which corresponds to a subcooling of 8 K. Experimental results lead to the following conclusions:

For relatively slow heating, the non-boiling heat transfers agree well with the values predicted by the well-known Dittus–Boelter equation. In the nucleate boiling regime, with relatively little increase in ΔT_L , the heat flux steeply increases to the CHF, where the heat transfer transitions to film boiling regime. Accordingly, the heat transfer can be regarded as steady-state.

For faster heating, the non-boiling heat transfer is enhanced because of the transient conductive heat transfer contribution for relatively low flow velocity, and the transient CHFs increase. The nucleate boiling heat transfer is unaffected by the heating rate and flow velocity. At higher flow rate, the transient CHFs become higher, and the transient convective heat transfer contribution in the non-boiling region diminished in this experimental measurement ranges of τ values. We confirmed that no direct transition from non-boiling to film boiling appear for shorter τ value, unlike with liquid nitrogen.

The increments of the transient CHF from the steady-state CHF would be independent of the flow velocity for the same test heater. For the same aspect ratio of L/D_h , the increment seems to be expressed by the same curve with the gradient of $\tau^{-0.5}$. For larger L/D_h , it is clarified that, although the increments are larger, they would be expressed by a curve with the same gradient of $\tau^{-0.5}$.

5. Acknowledgements

This work is supported in part by JSPS KAKENHI (20360127). The authors thank technical staffs of JAXA for technical assistance.

6. References

- [1] Coeling K J and Merte JR H 1969 *Journal of Engineering for Industry* **91** 513-524
- [2] Steward W G 1990 *Advances in Cryogenic Engineering* **35** 403-412
- [3] Graham R W, Hendricks R C and Ehlers R C 1965 *Advances in Cryogenic Engineering* **10** 342-352
- [4] Class C R, Dehaan J R, Piccone M and Cost R B 1960 *Advances in Cryogenic Engineering* **5** 254-261
- [5] Bewilogus L, Knoner R and Vinzelberg 1975 *Cryogenics* **15** 121-125
- [6] Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Kobayashi H, Naruo Y, Inatani Y, Kato K, Futakawa M, Kinoshita K 2010 *Journal of physics: conference series* **234** 032056
- [7] Shirai Y, Tatsumoto H, Shiotsu M, Hata K, Kobayashi H, Naruo Y, Inatani Y, Kinoshita K 2011 *Cryogenics* **51** pp 295-299
- [8] Tatsumoto H, Shirai Y, Shiotsu M, Naruo Y, Kobayashi H and Inatani 2015 *Journal of Superconductivity and Novel Magnetism* **28** 1185-1188
- [9] Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Kobayashi H, Naruo Y, Inatani Y, Kato K, Futakawa M and Kinoshita K 2010 *Proc. 23rd International Cryogenic Engineering Conference and International Cryogenic Material Conference* (Wriclaw) pp491-496
- [10] Tatsumoto H, Shirai Y, Shiotsu M, Hata K, Naruo Y, Kobayashi H and Inatani Y, *Adv. in Cryo. Eng.* **59A**, 2014, p. 403-412.
- [11] Tatsumoto H, Shirai Y, Shiotsu M, Naruo Y, Kobayashi H and Inatani Y 2014 *J. Phys.: Conf. Ser.* **568** 032017
- [12] Shiotsu M, Kobayashi H, Talegami T, Shirai Y, Tatsumoto H, Hata K, Kobayashi H, Naruo Y, Inatani Y 2012 *Adv. in Cryo. Eng.* **57A** pp 1059-1066
- [13] Tatsumoto H, Shirai Y, Shiotsu M, Kobayashi H, Naruo Y and Inatani Y 2015 in *ICEC-ICMC 2015, P3.3-7* (Enschede) (to be published)
- [14] Van Sciver S W 1986 *Helium Cryogenics* (New York: Plenum Press) p. 251
- [15] Sakurai A and Shiotsu M 1977 *Trans. ASME* **99** 547-553.